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Reply to commentary on the special issue Scaling up biofuels? A critical look at expectations, performance and governance

Ariane Goetz[a,*], Tim Searchinger[b], Tim Beringer[c], Laura German[d], Ben McKay[e], Gustavo de L.T. Oliveira[f], Carol Hunsberger[g]

[a] Institute for Advanced Sustainability Studies, Germany
[b] Woodrow Wilson School, Princeton University, United States
[c] Mercator Research Institute on Global Commons and Climate Change, Germany
[d] Department of Anthropology, University of Georgia, United States
[e] Department of Anthropology and Archaeology, University of Calgary, Canada
[f] Environmental Studies, Swarthmore College, United States
[g] Department of Geography, University of Western Ontario, Canada

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ABSTRACT

The special issue Scaling up bioenergy? identifies major policy expectations attached to biofuels production worldwide, and it provides systematic reviews of actual biofuel performance and governance in these areas. Papers address the extent to which policy expectations related to climate change mitigation, energy security, rural livelihoods and risk mitigation have been achieved, and the effectiveness of public and private governance in advancing sector sustainability. Building on these findings, the synthesis paper asks, "What next?" for countries wishing to advance national biofuel programmes as one option for the necessary divestment from fossil fuels. Among other sine qua nons, the special issue highlights the urgent need to downscale global energy demand, and to stop treating biofuels as an isolated sector. Goldemberg et al. (2018) query several aspects of our approach, from research design, data collection, to our recommendation to apply the "precautionary principle" in research as well as policy making. Unfortunately, Goldemberg et al. (2018) incorrectly portray our main argument. Moreover, they claim bias in our approach and mistakes in our empirical evidence, however, without bringing forward an evenhanded critique of research philosophy, methodology or referencing different empirical literature. We fully stand behind our research philosophy and findings presented.

1. Introduction

The special issue *Scaling up biofuels*? (2017)[1] identifies major policy expectations attached to biofuels production worldwide, and systematically reviews available evidence on actual biofuel performance and governance in these areas. The first set of contributing papers addresses the extent to which policy expectations for climate change mitigation, energy security, rural livelihoods and risk mitigation have been achieved. The paper by Searchinger, Beringer and Strong (Paper 1[2]) explores the potential of biofuels to contribute to climate mitigation. This is followed by a paper by Hunsberger, German and Goetz (Paper 2) examining biofuels and socio-economic policy expectations, including energy security; and a paper by Goetz, German and Hunsberger (Paper 3) on risk anticipation and mitigation in the biofuels sector. The second set of papers addresses the effectiveness of public and private governance in advancing sector sustainability. Oliveira, McKay and Plank (Paper 4) analyze the politics behind biofuel polices in the US, Brazil, and the EU and implications for sector development and sustainability; de Man and German (Paper 5) review literature on the effectiveness of certification in supporting sustainable energy transitions. The synthesis paper (Paper 6) asks, "What next?" for countries wishing to advance national biofuel programmes as one option for the necessary divestment from fossil fuels. Among other *sine qua nons*, the special issue highlights the urgent need to downscale global energy demand and to move beyond treating biofuels as an isolated sector (Table 1).

In their commentary, Goldemberg, Souza, Maciel and Cantarella (2018) query several aspects of our approach, from research design and scope, to the empirical validity of our findings and our recommendation

* Corresponding author.
E-mail address: ariane.goetz@iass-potsdam.de (A. Goetz).

[1] See Table of Content in Table 1.

[2] For reader orientation, we assigned numbers to the papers of the special issue. A numbered list of SI papers is provided in Table 1 at the end of this paper.

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Table 1
Content of Special Issue *Scaling up biofuels? A critical look at expectations, performance and governance* (2017).

Articles	Reference in the Reply to commentary
Goetz et al. (2017a). Scaling up biofuels? A critical look at expectations, performance and governance. *Energy Policy*, *110*, 719–723	Editorial
Searchinger et al. (2017). Does the world have low-carbon bioenergy potential from the dedicated use of land?. *Energy Policy*, *110*, 434–446.	Paper 1
Hunsberger et al. (2017). “Unbundling” the biofuel promise: Querying the ability of liquid biofuels to deliver on socio-economic policy expectations. *Energy Policy*, *108*, 791–805.	Paper 2
Goetz et al. (2017b). Do no harm? Risk perceptions in national bioenergy policies and actual mitigation performance. *Energy Policy*, *108*, 776–790.	Paper 3
Oliveira et al. (2017). How biofuel policies backfire: Misguided goals, inefficient mechanisms, and political-ecological blind spots. *Energy Policy*, *108*, 765–775.	Paper 4
De Man and German (2017). Certifying the sustainability of biofuels: Promise and reality. *Energy Policy*, *109*, 871–883.	Paper 5
German et al. (2017). Sine Qua Nons of sustainable biofuels: Distilling implications of under-performance for national biofuel programmes. *Energy Policy*, *108*, 806–817.	Paper 6

to apply the “precautionary principle” in support of renewable energy transitions. Unfortunately, Goldemberg et al. (2018) incorrectly portray our main argument, and discredit the rigor of the theoretical perspectives and epistemologies from which it emanates. We continue to stand behind the findings presented and the plurality of theoretical perspectives and epistemologies behind them, and take this as an opportunity to further clarify central arguments and the supporting evidence. In the sections that follow, we begin by responding to overarching concerns raised about the special issue as a whole (Section 2), then address key technical points raised by Goldemberg et al. (2018) in detail. Section 3 responds to comments on the paper by Searchinger et al. (Paper 1), to which the bulk of the critique is aimed (Section 3). Section 4 responds to comments on the social, economic, and ecological dimensions of biofuels and highlights insights to be gained from the social sciences. Section 5 discusses our choice to recommend the precautionary principle in the formulation, piloting and upscaling of biofuels production and use. We conclude by recapitulating main points and policy recommendations (Section 6).

We would like to thank the editors of Energy Policy for the opportunity to reply to the commentary, and in so doing address issues that are crucial to the debate on biofuels sustainability and policy; and Goldemberg and his colleagues for an engaging debate.

2. Response to overarching critiques raised and their broader implications

In this section, we address three overarching critiques: the use of different standards to the evaluation of biofuels and other fuel sources; the scope of technologies considered in the analysis (current vs. future); and questions about the evaluability (and validity) of different forms of scientific knowledge production.

Regarding the first, the commentary states that our analysis is biased because we do not apply the same assessment criteria to other energy sources (oil, wind etc.). Had our goal been to compare energy sources and we had applied evaluation criteria unevenly, this would have been a valid critique. Yet our goal for the special issue as a whole was not to compare energy sources, but to assess bioenergy on its own terms. For greenhouse gas analysis, our analysis did compare energy sources because bioenergy claims benefits over fossil fuels; in doing so, we compared the sources on the same terms. The fact that we endorse a precautionary approach to biofuels does not mean we think precaution is unnecessary for other energy sources (or policy arenas, for that matter). The commentary's argument is like saying that a study on the health effects of smoking must also present the problems associated with other addictive drugs.

The second critique concerns the failure to consider biofuel technologies that have promise but are not yet operational. With narratives about the potential of technologies in the pipeline to address deficiencies of first generation biofuels based on a host of assumptions, and history riddled with purported silver bullets that failed to live up to expectations, the best option for an analysis based on evidence was to focus on technologies that are currently operational. Thus, we consider the commentary's claim that advances in bio-refineries “*will lead* to industrial production processes that are zero CO_2 emission and also help food security” (emphasis added) speculative and premature.

The third point addresses the commentary's judgment that social considerations are irrelevant to evaluating bioenergy because they *“involve[s] preference, judgement, and philosophical views”* (p5). We think this statement misses several points. The first is the role of the social sciences in producing unique contributions to our understandings of agrarian and societal transformations. Understanding how political, economic and ecological systems influence bioenergy production and use, and how this production and use in turn influence the wider economic, social and ecological systems, is needed to improve policy and governance, as well as modelling and forecasting (Haberl, 2016; Sovacool et al., 2015; Mallaband et al., 2017; Sovacool, 2014; Moon and Blackman, 2014; see Section 4). And the social sciences are well suited to contribute unique and crucial insights into such endeavors. The second is the implied superiority of quantitative data and the biophysical sciences to the question of biofuel sustainability. Current theories recognize the partiality of all knowledges, while questioning the presumed objectivity of even the most empirical of sciences (Jasanoff et al., 1995; Latour, 1987; Latour and Woolgar, 1979). The articles of the special issue employ forms of theoretical and methodological rigor specific to their respective fields of inquiry, and in so doing provide a “public account” that is “honest, intelligible, and reasonable” and as objective as any other (Bird, 1998, 27).

The final point concerns the implied social neutrality of technology. Ample research in the field of science and technology studies now demonstrates the interrelation of technology, society and social change, including the influence of social and political conditions on the choice and production of technology (e.g., Green, 2001; Grubler and Riahi, 2010); the role of technology in producing socially and geographically uneven costs and benefits (Dauvergne and Neville, 2010; Obidzinski et al., 2012); and the social and ecological costs that can accompany allegedly sustainable technologies (e.g., Grubler, 2012; Fouquet and Pearson, 2012; Wilson, 2012; Fairhead et al., 2012; Janaun and Ellis, 2010). By uncovering broader dynamics, we highlight that the tendency to treat the biofuel sector as isolated industry, or as purely technical, comes at the cost of those marginalized in the process, while contributing to unintended consequences that undermine claims to green or socially responsible production (e.g., Fairhead et al., 2012; Fritsche et al., 2017, Haberl et al., 2010; externalization dynamics, see Section 4).

It is also worth mentioning that a phrase the authors pull out of the synthesis paper by German et al. (Paper 6), “*biomass derived agrofuels cannot be promoted in a way that meets social aims and environmental goals”,* is a misquote. The article actually states: "*Current levels of global energy consumption, even only in the transport sector, cannot be met by biomass-derived agrofuels in a way that meets social aims and*

environmental goals." While the mischaracterization suggests a blanket rejection of biofuels, the original phrase is a qualified statement about scale – a point which Goldemberg et al. (2018) appear to agree with when stating "[a] large scaling up in biofuel production will have to be followed carefully" (p 5).

3. Biofuels' contribution to climate mitigation under the dedicated use of land

The core point of the paper by Searchinger et al. (Paper 1) is that estimates of bioenergy potential from the dedicated use of land and claims that this bioenergy is low or no carbon are based on double-counting, in which land, biomass or carbon are treated as available for bioenergy while still meeting alternative uses. We address each of the concerns raised in the commentary roughly in order of importance.

3.1. Implicit claim that biomass is inherently carbon neutral

The commentary appears to argue that biomass is inherently carbon neutral because it would eventually all be put back into the atmosphere – and the only question is whether people use it to displace fossil fuels in the interim or not. But in fact, the world's terrestrial ecosystems are estimated to store on the order of 4 times the carbon present in the atmosphere (Ciais et al., 2014). This storage of carbon away from the atmosphere requires steady re-nourishment by carbon uptake from plant growth to replace losses from decomposition, and it is the aggregate balance that matters (Le Quéré et al., 2017).[3] How much carbon plants and soils store is therefore heavily influenced by agricultural and forestry activities, including bioenergy, and those activities have contributed roughly one third of the additional carbon in the atmosphere due to human activities. If the commentary's argument were correct, then it would apply not merely to bioenergy but to all land uses; and the world would be wrong to pay attention to carbon stored in forests and should stop counting the carbon released by land use and land use change as greenhouse gases.

The fact that burning biomass must release more carbon than burning fossil fuels is not based on the technology for burning either but based on the potential physical energy released by their combustion – just as some fossil fuels emit more than others – and is set forth in the IPCC National Greenhouse Gas Reporting Guidelines (2006), chapter 2, table 2.3, p. 2.18–2.19. The fact that some of this carbon dioxide might be recovered and used for other purposes with a form of carbon capture and storage is irrelevant, as the same is true for the carbon dioxide emitted by burning fossil fuels.

3.2. The Claims to abundant carbon-free land

The claim that abundant land is available for bioenergy relies primarily on the "exhaustive" "SCOPE" report by Souza et al. (2015), and for Brazil on a paper by Jaiswal et al. (2017). The Souza et al. report is actually a good example of double-counting. It repeats the error that goes back to the IPCC Assessment from 2001 of treating presently unused "potential cropland" (as estimated by the UN Food and Agriculture Organization, or FAO) as though it is inherently carbon-free land for bioenergy use. Although the alternative uses of land are the dominant issue with bioenergy, this lengthy document devotes only a couple of paragraphs to land availability, of which the core is three sentences and relies exclusively on this FAO estimate.

> "At a global level, land is not a constraint. Land available for rainfed agriculture is estimated to be 1.4 Bha of 'prime and good' land and a further 1.5 Bha of marginal land that is 'spare and usable'. Around 960 Mha of this land is in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha) with much, if not all of it, currently under pasture/ rangeland." (citations omitted)

The FAO itself and others have called these figures serious overestimates of potential cropland for a variety of reasons (Alexandratos and Bruinsma, 2012; Young, 1999), but the real flaw is that potential cropland unused for cropping is not unused for other purposes. The FAO is not claiming that an area roughly four-times the size of the continental U.S. is sitting around bare. After excluding denser forest, this land overwhelmingly falls into two categories: woody tropical savannas such as the native Brazilian Cerrado, and the world's better and wetter grazing lands. Tropical savannas are not only areas of high biodiversity, but also have high carbon content (Popp et al., 2014), and papers that analyze both the carbon benefits and costs of using them for biofuels estimate long carbon debts (Fargione et al., 2008; Gibbs et al., 2008; Searchinger et al., 2015). Notions that this land is 'spare and usable' also ignore the fact that this land is typically owned/claimed under customary systems of tenure, and supports crucial livelihood functions that would be impacted by its conversion (Alden Wily, 2011; Campbell, 1996; German and Gumbo, 2013; Shackleton and Shackleton, 2004).

The world's wetter grazing lands not only provide biodiversity and store carbon, but they also produce milk and ruminant meat. The Souza et al. (2015) report correctly points out that there is substantial technical potential to intensify grazing operations (as there is for crops as well), but for two reasons, that does not make grazing land a carbon-free, or advisable asset for bioenergy.

- First, according to most diet projections, the world will demand 70% or more ruminant meat and milk by 2050 (Searchinger et al., 2013). Even factoring in vast intensification, most analyses project expansion of global pasture land by 2050 by hundreds of millions of hectares (Bajželj et al., 2014; Popp et al., 2017; Schmitz et al., 2014). To put the challenge in perspective, if Brazil maintains all its existing pasture and doubles its output per hectare, Brazil will only supply 15% more beef for the world (HLPE, 2013). At this time, pastureland is expanding not only in total area but in shifting from drier, hillier, less productive land to more productive and carbon-rich lands (Aide et al., 2013). Unless and until that changes, there can be no net pasturelands available for bioenergy (even ignoring all social considerations).
- Second, even if some combination of massive intensification and dietary shifts were to reduce total demand for pasture land, the use of abandoned pasture for bioenergy would still come with the cost of not using that land for other purposes. Abandoned pasture land, particularly if wet enough to be relatively productive, can typically regrow forests, and as pastureland shifts regionally and within regions, the reforestation of abandoned agricultural land explains much of the reforestation in Europe (Alcantara et al., 2013; Kuemmerle et al., 2016), in the Eastern United States (Albani et al., 2006), and in Latin America (Aide et al., 2013). A correct calculation of the benefits of bioenergy from net displacement of fossil fuels must count this foregone sequestration as a cost. As shown by Searchinger et al. (Paper 1), counting this foregone sequestration, producing bioenergy on abandoned land almost always results in a net increase in atmospheric carbon, and even with the most favorable assumptions, generates far from a truly low carbon fuel source.

The claim in Jaiswal et al. (2017) that abundant free land is available in Brazil for bioenergy is also based on this view that pasturelands are free.

Although the basis of the latest IEA Bioenergy Roadmap cited by the comment cannot be traced – as it cites unpublished presentations in a

[3] The fact that any particular atom of carbon in plants and vegetation is likely at some point to spend time in the atmosphere does not negate the importance of terrestrial carbon storage; for similar reasons, the fact each atom of carbon in the air will likely spend some time in plants and soils does not negate its effect on warming.

conference proceeding – the paper by Searchinger et al. (Paper 1) shows how similar analyses by the IEA are all secondary claims, relying on studies such as Cai et al. (2011), or Hoogwijk et al. (2005), which in turn make similar errors by assuming that much of the world's woody savannas and pasturelands are free for bioenergy use. In fact, these underlying papers never calculate carbon costs for using any land for bioenergy. Instead, they assume that land, and biomass, are inherently carbon-free assets to be used for bioenergy and exclude some land only based on broader "sustainability" or food competition grounds.

A figure of 150 EJ or more of potential bioenergy per year suggested by the commentary compares with roughly 71 EJ of gross energy available in all the world's annually harvested crops (Searchinger and Heimlich, 2015), and roughly 35 EJ in the world's annual wood harvest (Krausmann et al., 2008). Demand for both crops and wood products are growing rapidly. Yet as noted above, agricultural occupation and forestry are responsible for roughly one third of carbon people have added to the atmosphere (Le Quéré et al., 2017). These massive estimates of bioenergy potential by the commentary and others relative to all existing human plant harvests suggest a basic error somewhere, and by tracing these estimates back to the underlying studies, the paper by Searchinger et al. (Paper 1) confirms these errors lie in double-counting land, biomass and carbon.[4]

3.3. Solar alternatives

Among the alternative uses of any "available" lands are using lands for a chemical, solar conversion pathway such as PV rather than bioenergy, which is a photosynthetic pathway. Searchinger et al. (Paper 1) calculate that on three quarters of the world's land, the conversion efficiency advantage, and therefore land use efficiency advantage, is at least 100–1, and it would be anywhere from 30 to 60 times that of Brazilian sugarcane ethanol depending on the spacing of PV arrays. The commentary claims that the efficiency advantage of solar or sugarcane is at most 10–1 if one considers the by-products of using bagasse. In fact, as we state explicitly in the supplement, we did consider these by-products, but the production of the ethanol also requires substantial quantities of energy for fertilizer, for tractors and for heat for refining the sugarcane. When counting both energy by-products and these fossil energy inputs, analyses by Argonne Laboratory and the EU Joint Research Centre among others find that the net energy generated by sugarcane ethanol is actually a little *less* than the maximum energy released by burning the ethanol (Argonne National Laboratory, 2014; Edwards et al., 2014). To be conservative, we credited sugarcane ethanol with 100% of the energy in the ethanol by assuming that all of the energy required in the production process is "offset by an electricity energy credit from burning sugarcane bagasse."

How then does the article Horta Nogueira et al. (2013), as claimed by the commentary, find "only" a 10–1 ratio? The answer is partially that it did not. The numbers in that paper for delivered energy comes to a ratio of 22–1.[5] But the real problem is that this paper excludes from its calculation any and all energy to produce the ethanol. In fact, only 15% of the energy this paper attributes to sugarcane ethanol production comes from the energy in the ethanol itself. Most of the energy counted by this paper as a net gain in energy is the energy in the bagasse that is burned for heat to drive the refining process of the sugarcane itself. That does not result in a net contribution to energy supply from sugarcane ethanol production.

The commentary also misses the more basic point, which is that sugarcane ethanol can achieve even 0.2% efficiency only because it is grown on some of the world's most productive land, land which could produce sugarcane for food, soybeans and many other crops at high yields. An even bigger advantage of PV is that it can be used without any yield penalty on much less productive land. Although, as the paper by Searchinger et al. (Paper 1) discusses, solar energy can face storage constraints,[6] storage technologies are evolving fast, and ultimate solutions to the storage problem would have to be fantastically land-inefficient to cancel out the land advantages of solar pathways. At a minimum, it makes little sense to commit to bioenergy now. The world still has massive potential to expand solar without such constraints, storage is evolving both in practice (e.g., Frankel and Wagner, 2017) and technically (IRENA, 2015) and as discussed above, any use of bioenergy from dedicated use of land has large greenhouse gas opportunity costs.

3.4. Additionality

Searchinger et al. (Paper 1) describe the systematic ways in which papers have counted land, biomass or carbon twice, and the above describes some of them. Typical lifecycle analyses (LCAs) do this in a crude way. They assume that the biofuel uses a crop, such as maize, that would be grown anyway. They then contradictorily count the carbon absorption of the crop as an offset for the carbon released by burning the biofuel although nothing that would occur anyway can count as an offset. Sugarcane LCAs employ the same practice. This commentary asks us to imagine instead that sugarcane used for ethanol is replacing pasture, which probably does happen directly sometimes, but no sugarcane LCAs to our knowledge deduct the carbon that would be absorbed by the pasture's grass from the offset. So even on this simplistic assumption of sugarcane replacing pasture, there is some double-counting of biomass.

But the bigger error is that this type of analysis is less double-counting biomass than double-counting land. As explained in Paper 1, for any particular hectare a high biomass-yielding crop, such as sugarcane or maize, can replace a low-biomass crop, such as lettuce, and that particular hectare of land will produce more biomass. But so long as the world continues to demand low-yield crops like lettuce, it must recreate that low-yielding crop elsewhere. If it does, there is no likelihood of a global increase in the production of biomass. It is true that one response might be that the world consumes less lettuce, but in that case, the analysis is double-counting land unless it tells the world that the benefits from bioenergy result from producing less lettuce. For this basic reason, switching a hectare from other land uses to sugarcane for ethanol is not any more of a carbon sequestration strategy by itself than switching food crops from lettuce to maize, or for that matter, from maize to sugarcane.

It is true that highly managed sugarcane will produce more biomass than most pastures, but the world uses pasture because it is a cheap way of producing beef, milk, and goat and sheep meat. That is why the average Brazilian consumes more beef than the average resident of any

[4] Note: It is not possible to simply breakdown the double-counting between land, biomass and carbon as they (a) overlap and (b) vary between papers doing so. For example, if a paper treats forest as a source of bioenergy, the paper both double-counts forest (if it does not reveal that the bioenergy will reduce global forests) and double-counts the carbon in the forest if it claims, implicitly or explicitly, that the bioenergy is carbon-neutral and does not count the loss of carbon storage and ongoing sequestration in the forest as a carbon loss. Because each paper has its own form of double-counting, it is also not possible to make a breakdown. The different forms of double-counting are discussed in the underlying, Searchinger et al. paper (Paper 1).

[5] The authors apply an average sugarcane yield of 82.4 t/ha, an ethanol yield of 88.7 l/t, an ethanol energy content of 22 MJ/l, and a combustion efficiency of 30%. This results in 0.05 TJ/ha. According to the authors, by-products of sugarcane processing (bagasse and harvest wastes) contain an additional 4.65 GJ/t which can be used for the co-generation of electricity and heat. Assuming a conversion efficiency of 69%, this feedstock adds a further 0.26 TJ/ha. For PV, the authors assume an average insolation of 2000 kWh/m^2, a conversion efficiency of 15%, an electric car battery charge/discharge efficiency of 80%, and an electric motor efficiency of 80%. In total, this results in 6.9 TJ/ha produced. So according to this calculation, PV produces 22 times more energy per ha than sugarcane.

[6] The negative social and environmental impacts documented for the disposal stage of the life cycle are surmountable, but must also be considered if the full impacts of alternative energy technologies are to be taken into account (Mulvaney, 2013).

other country. Although pasture management can and must be intensified, as we discuss above, that is already needed on a massive scale to avoid further expansion of pastures, and any spare hectare of pasture would have carbon opportunity costs.

3.5. Biofuel production today

Lastly, the commentary suggests biofuel production only occupies 15 Mha of land and has not been directly displacing natural habitats. The fact that biofuel production is probably mostly directly supplied from existing cropland is more or less irrelevant to its effects, because what matters is its contribution to the overall demand for land. Although the 15 Mha number is an underestimate – compare Rulli et al. (2016) (41 Mha) and HLPE (2013) (2–3% of global cropland, i.e. 32–48 Mha assuming 1600 Mha of global cropland) – estimating the hectares used for bioenergy is inherently ambiguous not only because there are different ways to account for by-products, but also because it is not clear what yields should be used. A hectare of maize in the U.S., for example, has twice the global yield and more than four times the yield of land in Africa, so attributing maize ethanol to U.S. yields means fewer hectares but each hectare has four times the significance for global food supplies as an African hectare. More useful is to count the percentage of crops diverted to biofuels. As of 2010, biofuels used roughly 5% of the energy in all the world's crops and produced roughly 0.5% of global delivered energy (Searchinger and Heimlich, 2015). As these ratios show, producing more than such a small fraction of global energy would require large shares of the world's grains and vegetable oils and confirms the costs of dedicating land to producing bioenergy.

4. Socio-economic expectations and risks of biofuels production and use

The articles by Hunsberger et al. (Paper 2) and Goetz et al. (Paper 3) and Oliveira et al. (Paper 4) aim to assess the conditions and effects of (un)sustainable production and use patterns. Goldemberg et al. (2018) critique our assessments of “small-holder inclusion, decentralized system, rural development, pro-poor development purposes” by implying that these articles (Papers 2–4) are biased or unscientific, as stated above. In this section, we wish to highlight the ways in which our approach provides for a more meaningful understanding of actual biofuels’ sustainability performance that can inform policy making and forecasting. To illustrate our point, we address two statements made by Goldemberg et al. (2018) in reference to our social and political-economic analyses, namely the statement that the sugarcane ethanol industry has “increased GDP and improved education… in the State of São Paulo”, and the statement that it has generated “one million direct jobs.” As shown below, Oliveira et al. (Paper 4) highlight injustices faced by over half a million people which tend to be overlooked by generalized statistical reports or misinterpreted through the selective focus on a narrow set of socio-economic indicators of a limited region of a country.

The focus on socio-economic improvements in São Paulo appears justified by the fact that the sugarcane ethanol industry is focused primarily in this state, yet it overlooks the fact that agricultural and industrial development is interrelated and uneven across regions (Storper and Walker, 1989; Harvey, 2006). Taking a regional perspective, the development of the sugarcane ethanol agroindustry in São Paulo has occurred in contrast to the collapse of the same industry in the Brazilian northeast (Compeán and Polenske, 2011), and has indirectly benefitted from growing regional inequality through the underemployment and displacement of workers from the northeast to São Paulo state and the re-channeling of finance (Storper and Walker, 1989; Lehtonen, 2011; Pinheiro, 2013; Oliveira, 2015; Carvalho, 2017). Thus, the influx of cheap labor from the Northeast to São Paulo subsidizes the further development of the industry in that state, which reinforces the relative divestment from rural development in the northeast, reinforces capital flows into São Paulo's sugarcane/ethanol sector, and aggravates regional inequalities in terms of GDP growth, education improvements, and various other socio-economic indicators (Storper and Walker, 1989; Lehtonen, 2011; Pinheiro, 2013; Oliveira, 2015; Carvalho, 2017). This is not to imply that the sugarcane/ethanol industry in Sao Paulo is responsible for these trends, but rather that the *net* social benefits and costs cannot be evaluated based on a single region alone (see also Harvey, 2006).

Second, while Goldemberg et al. do not provide a reference to the claim that “ethanol from sugarcane in Brazil generates one million direct jobs”, or indicate over what period this number has been estimated, it may indeed be the case if we include the entire sugarcane industry, including cutters, transport drivers, millers, office administration and others in the sugarcane-sugar-ethanol industrial complex since the 1970s. Nonetheless, two critical factors must be taken into account. First, roughly half (500,000) of the employment generated by sugarcane-ethanol industrial complex represent cane cutters and other field-based sugarcane workers. The labor conditions of sugarcane workers, particularly in Brazil, have been well-documented (see Alves, 2006, 2007; Galiano et al., 2012; Lehtonen, 2010; Thenório, 2008: Reimberg, 2009; Ribeiro, 2013; McKay et al., 2016). Among the worst in the plantation sector globally, they have often been equated to slave-like conditions whereby “labor inspectors in Brazil judged conditions to be degrading and employment relations to involve a significant element of unfreedom” (McGrath, 2013, 32). As pointed out in Oliveira et al. (Paper 4) over 10,000 workers were rescued from conditions analogous to slavery in the sugarcane/ethanol sector from 2003 to 2010 (p. 769). In other words, the statement that the industry “generates one million direct jobs” tells us nothing about the type or conditions of these jobs and points to the need for depth and attention to detail to qualify what this actually means. In this context rigorous social science can indeed raise the level of understanding on these complex socio-economic factors beyond purely subjective considerations.

Another point is missing in this context: in addition to poor working conditions, sugarcane cutters are being increasingly displaced by mechanization. One machine displaces roughly 80 sugarcane workers in Brazil (Ribeiro, 2013), and as Hunsberger et al. (Paper 3) show, the number of workers employed in sugarcane production in Brazil has decreased drastically in recent years.[7] Brazil has also been moving to phase out burning in sugarcane in the name of air quality and public health, which will significantly reduce demand for manual cane cutters as the industry transitions to a mechanized harvest (Ninô de Carvalho n.d.). The Brazilian Sugarcane Industry Association (UNICA) suggests that these workers “will have to migrate to other activities” (UNICA, 2010, 73). Yet questions remain as to where and how these surplus populations will be absorbed in the economy. As Oliveira et al. (Paper 4) point out, RenovAç ão, which was established to provide training to displaced sugarcane cutters has been quite unsuccessful, providing training for just 5700 displaced workers in six years, or just 14% of its goals of 7000 workers per year (UNICA, 2016). Furthermore, a recent article by Novacana, a news website typically supportive of the sugarcane-ethanol industry, documents how the exclusion of sugarcane cutters due to mechanization has left many without a means to reproduce their livelihood. It is also noteworthy that soy-based biodiesel production (predominant in Brazil) generates even fewer employment opportunities, and displaces smallholders over far larger areas than sugarcane production - producing net social effects that may be even worse (Oliveira et al., 2016). For the Brazilian biofuel industry to rest soundly on its claims to employment benefits, it therefore needs to completely restructure labor conditions (to include social security,

[7] The number of workers employed in sugarcane production has decreased by 62% nationally as a result of mechanization (Dufey, 2008; Ortiz and Rodrigues, 2006), and the employment intensity of unskilled workers in south-central Brazil fell from 57 to 40 workers per 1000 ha from 2007 to 2009 (Baccarin et al., 2011).

benefits, minimum wage, safety measures, etc.), and to take seriously the welfare of those displaced through mechanization.

5. Employment of the precautionary principle

The commentary by Goldemberg et al. (2018) states that “energy is an essential ingredient of development” with both negative and positive social and environmental effects, and concludes that, “One cannot therefore adopt prematurely for biofuels a ‘strong precautionary principle’ and will have to learn by experience what is possible to achieve with them” (p 5). Because energy is central to development, and related social and environmental effects often irreversible, it is crucial that the effects produced by introducing or expanding any given energy source be fully evaluated at each stage, thereby enabling an evaluation of whether the costs are worth bearing for the sake of both intended and actual benefits. Otherwise, we would be exploring the mere possibility (rather than sustainability) of biofuels production and use. Only a precautionary principle supported by multiple lines of evidence can allow researchers and policy makers to observe developments and evaluate their evolving implications – social, economic, environmental – with the necessary rigor (Stirling, 2014; Fouquet and Pearson, 2012). The problems identified by Searchinger et al. (Paper 1), however, are not just about risk, they are about math, and calculations of greenhouse gas consequences would be the same whether or not one adopts a precautionary principle. Yet in adopting a precautionary approach grounded in proper accounting methods and early evaluations of impact, the social and environmental costs that might otherwise be produced (e.g. through blind application of policies grounded in overly optimistic assumptions) can be avoided.

6. Conclusion and policy implications

Our reply responded to key critiques voiced in the commentary by Goldemberg et al. (2018) about the special issue *Scaling up biofuels*? (2017). We used the opportunity to clarify the mischaracterization of our main argument, and to underline the theoretical rigor and empirical validity of different research approaches and their contribution to the study of sector sustainability. The reply also probed the commentary's assumption of neutrality and future potential of technology in sustainable (bio)energy transitions; and it addressed the need for a precautionary principle in energy research and policy. Most importantly, it spoke to the commentary's concerns about the validity of empirical evidence regarding the high opportunity costs of the dedicated use of land, and the socio-economic implications of biofuels production and use today.

Our response has reaffirmed that multiple sustainability problems of biofuels production and use persist, both from the mathematical viewpoint of the dedicated use of land, and from the empirical viewpoint of socio-economic injustices and risks involved. Further, the reply has emphasized the benefits to be gained by complementing statistical data with other theoretical perspectives and epistemologies for a more meaningful understanding of the quality of conditions, interlinkages, and outcomes. To date, our research shows that policies and strategies to mitigate risks are often poorly equipped to actually address the particular challenges of sector sustainability, and they often lack any context-adjusted vision for sustainable pathways of development and transition.

We recommend to policy makers and researchers alike to recognize available historical research and data on energy transitions which warns us about being overly optimistic, and demands us to go forward incrementally: “*The perhaps most important conclusion pertaining to the next energy transition is a strong caution against pre-mature scaling up of technologies and industries, shortcutting the essential early period of experimentation and learning*” (Grubler, 2012, 14; see also Fouquet and Pearson, 2012). Research suggests that at current levels of consumption, energy transitions in general pose serious challenges to economies and – in the case of biofuels – to the ecological and social functions of rural landscapes, even in those countries that use more efficient technologies and/or are able to externalize their consumption to other countries' sites of production (Jefferson, 2018; Wilson, 2012; Turnheim and Geels, 2012). Against this background, and for the sake of sustainability, a precautionary approach is essential for ensuring awareness of biofuel developments and their early performance; bringing a nuanced understanding of what works, what doesn't and why; and exploring what can be done to improve outcomes and mitigate risks, while analyzing broader implications for energy transitions and the role of biofuels in it (also see Stirling, 2014). In our synthesis paper, this principle led to the distillation of two key *Sine qua nons* things: to recognize that at current levels of global consumption, even if only within the transport sector, sustainable bioenergy production and use is impossible; and, to account for the feedback loops with other sectors of society in biofuel policy and evaluation.

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